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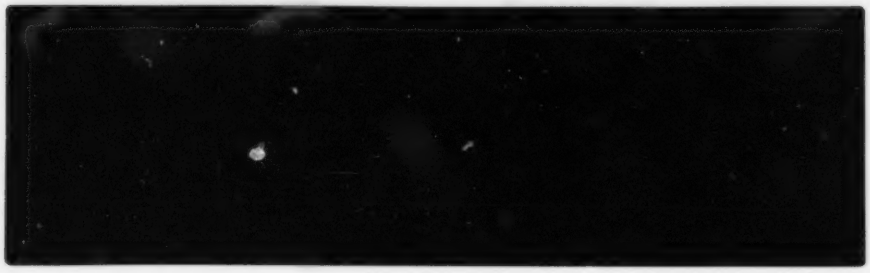

Canada

The safety of mine-shaft wire-ropes —
cooperative work by Canada and the U.S.A.

L.B. Geller, G.L. Anderson, A.J. Miscoe, and E.W. Mitchell

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ABSTRACT

Concern with safety in mines is a constant preoccupation of mining authorities the world over. It is also one of the many subjects with which the ongoing cooperative research work undertaken, for many years, by United States and Federal/Provincial Canadian organizations, deals. This report covers one aspect: electro-magnetic (EM) examination of mine-shaft wire-ropes. It is an example of the success cooperative work can achieve.

The authors of this report examine the data contained in the Ontario Ministry of Labour's uniquely extensive rope-test data-bank; they augment these by information obtained from industrial and laboratory sources, both in Canada and the U.S.A. As a result they conclude that, while EM testing has greatly increased the safety of mine-shaft hoisting, work to further improve the accuracy of this process — especially in certain corrosion and rope-construction related areas — is both necessary and urgent.

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The safety of mine-shaft wire-ropes — cooperative work by Canada and the U.S.A.

by

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INTRODUCTION

In situ non-destructive testing of mine-shaft wire-ropes, with EM type instruments, has been practiced internationally for many decades. Over the years a range of much improved instruments was developed by scientists in a number of countries including, inter alia, Britain, West Germany, France, Belgium, Switzerland, Poland, Chechoslovakia, the U.S.A. and Canada. It is generally acknowledged that the safety of mine-shaft hoisting has increased severalfold since the use of EM rope testers has become widespread. Unfortunately, however, wire-rope failures, involving serious material damage if not loss of life, still occur. This happens even in situations where regulatory testing requirements have been followed to the letter, and where the failed ropes had been declared fit for further use.

We examine some of the factors that are likely to be at the root of this serious problem. In particular:

(1) we summarize an analysis of a uniquely informative data-bank, compiled during the past three decades, or so, by the Wire Rope Testing Laboratory of the Ontario Ministry of Labour (OML) in Canada, as well as of data obtained from other Canadian and U.S. sources. Our objective is (a) to quantify just how accurately EM instrument based, *non-destructive test (NDT)* estimates of wire-rope

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strength-losses, match those established by comparative *destructive testing (DT)*, and (b) to compare the accuracy levels attained with different commercial variants of these EM testers;

(2) we summarize a comparison of the regulatory requirements established by a number of mining-authorities. Our objective is to examine (a) the very wide diversity of technical demands placed upon the users of EM instruments; (b) whether, in fact, all of these requirements can be met at the present state of EM instrument development, and (c) the regulatory requirements dealing with the training of the instrument operators.

BACKGROUND

While we are cognizant of the significant amount of literature dealing with the general subject-area of non-destructive testing with EM instruments, we believe that only a few of these papers need to be referred to here. A major report (Young et al 1947) is of interest, due to the exceptional amount of practical information it contains, and because it establishes the point of departure for EM instrument research in Canada. Another very important report — one of the very few containing actual test data of the type being discussed in this report — describes the project conducted in 1978 by Britain's Safety in Mines Research Establishment (SMRE) in Sheffield, England. This work involved the comparative examination, under laboratory conditions, of five locked-coil and two stranded wire-ropes with six different European EM testers. Results were described elsewhere (Commission 1978, Safety and Health 1981). While very relevant, these tests were performed for slightly different reasons than are of interest at present. In 1978 the accuracy with which the various testers could detect the precise nature and location of the Local Faults (LF) in the ropes was examined. Loss of Metallic Area (LMA) and Loss of Breaking Strength (LBS) — of major concern to us — were of little, or no interest.

One other set of past papers (Rice and Jentgen 1983, Jentgen et al 1984) also deals with extensive data of the kind we examine. In fact it is an earlier example of cooperation between Canada and the U.S.A., insofar as these papers are also based on the OML data bank, as it existed in 1983. This work was a major, as well as a "first" effort to statistically analyse the mass of available data. One of the findings was the conspicuous absence of the EM predicted strength from among several independent variables — with strength loss as the dependent variable — thus reflecting the initially poor fidelity of the early EM testers, and the vicissitudes of a newly emerging technology. Or, to paraphrase others (Weischedel 1985) in the same context: *AC testing has been*

practised in North America for many years. It suffers from serious deficiencies such as complicated operation, insufficient quantitative resolution, bad signal-to-noise ratio, and therefore, unreliability. A recent study (Rice and Jentgen 1983) demonstrated the relative ineffectiveness of this method.

While the 1983 and 1984 papers examined the entire body of report-data (some 1670 out of an overall total of more than 5500) we, on the other hand, choose to severely limit our scope of data-selection. First, we limit our analysis to strength-loss data alone, ignoring all other available data (such as rope-extension values, visual corrosion and lubrication ratings, and wire torsional test-results). Second, even of these data we choose to omit many, and use only (a) those DT/NDT data-pairs where it is reasonably certain that they refer to identical rope-lengths — a certainty lacking in case of many of the data points, or (b) those data-pairs where the foregoing consideration is of secondary importance. This is the situation in case of long rope sections with little change of conditions in them, or whenever safety considerations are of paramount importance. In the latter case, it will be noted, it is of less importance whether the "estimated" (i.e., NDT determined) and "true" (i.e., DT determined) weakest links are in the identical rope section, or not, as long as the DT/NDT data-pair is from the same rope. Consequently, most of the data-pairs analysed by us are the maximum strength-loss data-pairs, isolated from among a number of results obtained on the same rope.

BENCHMARK PARAMETERS

The mine-shaft wire-rope retirement criteria — as mandated by MSHA in the U.S.A. (Office 1988) and by most provincial regulatory authorities in Canada (e.g., Occupational Health and Safety 1987), — involve, inter alia, rope-strength (rather than metallic-area) losses. Consequently, one major focus of our paper is to quantify the accuracy with which various EM testers can determine a mine-shaft wire-rope's loss of breaking strength, and thus by extension, the safety and economy with which these ropes are currently being retired. The benchmark parameters used by us for the present analysis are, therefore, a reflection of these regulations (Occupational Health and Safety 1987, Office 1988) as well as of Ontario's supplementary "Performance Requirements for Electro-Magnetic Mine Shaft Rope Testing Devices" (Geller et al 1988). It is for this reason:

(a) that we consider a strength loss of 10% for hoist ropes, 15% for balance ropes, and 25% for guide and rubbing ropes to be of "critical" importance. As an extension: our analysis is centered on "true" strength losses in the order of at least 10%, with lesser values being of secondary interest at the moment — although we also

analysed a number of results obtained with "Best Piece" rope samples, because they are of special importance in case of locked-coil ropes;

(b) that we accept the regulatory requirement that mine-shaft ropes be examined in situ throughout their entire working length, by a competent person using an appproved EM testing device (in Ontario's case approved by the Mining Health and Safety Branch Director of the OML), and — as an extension — that we are aware of the additional implications our present analysis may have in conjunction with future decisions of this nature;

(c) that we calculated the loss of rope breaking-strength as a percentage of the original Certificate of Test strength value (and not as a percentage of some *Best Piece* found in a current rope);

(d) that we report an EM instrument estimate-based strength-loss value — as established on an in situ rope with a confidence level of 95% — as being "acceptable" if it is within four percentage points of the actual rope strength, where the latter has been determined by an approved wire-rope testing laboratory (such as, for example, the OML's in Toronto).

DATA ANALYSIS

(1) Statistical analysis

Complete details of the wire-ropes examined, and of the test-data analysed by us, are much too voluminous to include in this report. We have, however, assembled them in an easily accessible format (Geller et al 1988, Anderson and Farley, Ruff and Anderson, Poffenroth and Sheridan 1988, Poffenroth and Sheridan 1986). After restricting our data-choice (see BACKGROUND) 475 data-pairs were retained from the wealth of information available to us from Canadian and U.S. sources. Of these 49% were obtained with locked-coil (LC) ropes, 8% with non-rotating (NR) rope constructions, and 43% with stranded (STR) ropes. Three Canadian EM instruments were used: for 61% of NDT data the Rotesco AC, for 18% the Rotescograph, and for 21% the Magnograph. This distribution reflects, to some degree, the length of time for which these instruments have been in commercial use. The AC tester measures LMA only, while the other two instruments produce both LF and LMA traces. A summary of the results is listed in Table 1, and illustrated in Figures 1 to 7.

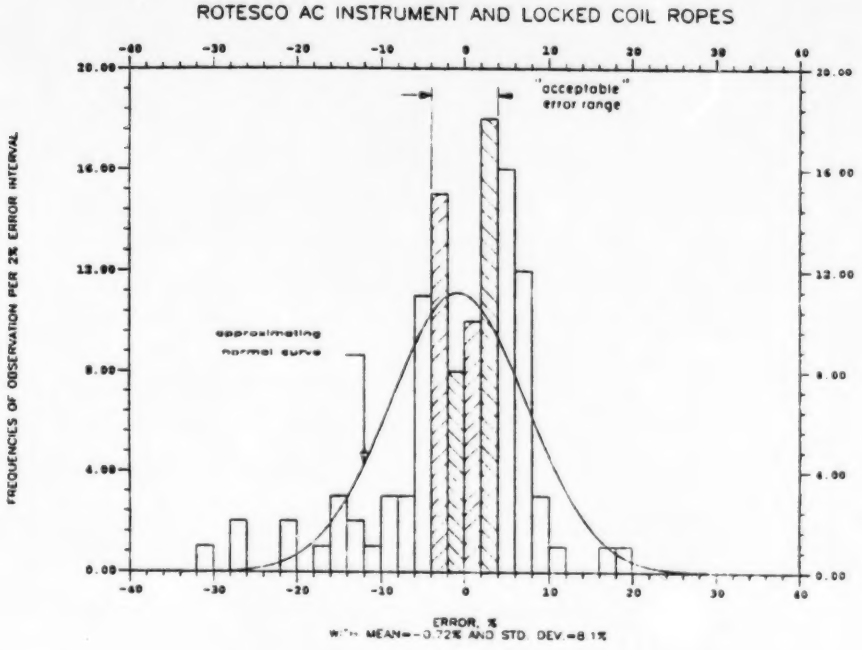
ROTESCO AC INSTRUMENT AND LOCKED COIL ROPES
"acceptable" error range
approximating normal curve
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
ERROR, %
WITH MEAN=-0.72% AND STD. DEV.=8.1%

Fig. 1 — Error% vs frequencies of observation (113 altogether), and the approximating normal curve — locked coil ropes and Rotesco AC instrument

A breakdown of the data — to further investigate instrument characteristics, with special regard to the "critical" 10% LBS value — is listed in Table 2.

It will be noted that in case of the locked-coil and stranded ropes an average of 36% of all Rotesco AC measurements are within the "permissible" (in the sense of Ontario's Performance Requirements) ±4% accuracy range. In case of the Rotescograph this figure is 61%, and with the Magnograph it is 57%. Unfortunately, many more data-pairs were available for the AC instrument, than for the other two. This is particularly so in case of the non-rotating rope constructions. Nonetheless, to give a clearer overall picture of the results, and to give a clearer overview, we grouped the test results, analysed them statistically, and plotted them accordingly.

It is the usual statistical procedure to fit experimental data to normal distribution whenever possible, because statistical theory is most developed for this distribution curve. It gives an indication of how well the normal distribution approximates the experimental data. The statistics used by us are based on the premise that the data follow the normal distribution. Although it may appear that the normal distribution is not a precise descriptor of the data, it should be understood that the statistical functions used in our analysis are not significantly affected by moderate deviations from the normal distribution.

Table 1

Analysis of test data — a summary

EM instr. used — results obtained	Rope construction		
	LC	NR	STR
Rotesco AC —			
total # of DT/NDT data-pairs, Σ	113	31	144
$\overline{X}$ of all errors, %	-0.72	-16.0	-6.5
S of all errors, %	8.1	16.9	11.2
"acceptable" data**, % of Σ	37	33	38
Rotescograph —			
total # of DT/NDT data-pairs, Σ	51	1	34
$\overline{X}$ of all errors, %	1.1	—	0.10
S of all errors, %	4.0	—	8.0
"acceptable" data**, % of Σ	65	0	56
Magnograph —			
total # of DT/NDT data-pairs, Σ	69	6	26
$\overline{X}$ of all errors, %	0.83	-3.3	0.23
S of all errors, %	4.8	6.9	10.0
"acceptable" data**, % of Σ	64	83	50

**: % of total NDT data — i.e., of "estimated" strength-losses — that are within the "permissible" (in the sense of Ontario's Performance Requirements) $\pm 4\%$ error range; the NDT=0 values are omitted here, and considered elsewhere.

We tabulate two important parameters (Table 1). One is the mean, or average value, $\overline{X}$, of the data. It indicates where the range of errors is centered. In other words if $X_1, X_2, \ldots\ldots, X_i, \ldots\ldots X_n$ are the errors of the n data-pairs, then

$$\overline{X} = \frac{1}{n} (X_1 + X_2 + \ldots\ldots + X_i + \ldots\ldots + X_n)$$

We define the Estimating Error as the difference between the actual (or "true") loss of a rope's breaking-strength as determined destructively, and the "estimated" loss of breaking strength, as determined non-destructively on the basis of the EM instrument-chart traces. Its value is:

Table 2

Analysis of test data — a breakdown of the data

Type of instrument ⟶	Rotesco AC			Rotescograph			Magnograph		
Rope construction ⟶	LC	NR	STR	LC	NR	STR	LC	NR	STR
Total # of data-pairs, Σ	113	31	144	51	1	34	69	6	26
% of Σ with + error	54	26	24	57	100	53	62	17	46
% of Σ with −error	46	74	76	43	0	47	38	83	54
Of all data-pairs with + error:									
% in DT<10% range	93	88	91	97	0	67	81	0	50
% in DT≥10% range	7	12	9	3	100	37	19	100	50
Of all data-pairs with − error:									
% in DT<10% range	54	9	21	68	0	15	58	0	21
% in DT≥10% range	46	91	79	32	0	85	42	100	79
Of total DT data:									
% in DT<10% range	74	32	38	88	100	47	83	0	35
% in DT≥10% range	26	68	62	12	0	53	17	100	65
Of total data in DT<10% range:									
% "acceptable"	56	90	67	62	0	69	60	0	56
Of total data in DT≥10% range:									
% "acceptable"	17	10	28	83	0	39	83	83	47
Of total NDT data:									
% with NDT=0	22	3	6	33	0	6	32	0	0
of these:									
% with +DT	88	100	22	94	0	0	77	0	0
% with −DT	12	0	78	6	0	0	23	0	0

$$\text{Error, \%} = (\text{DT, \%} - \text{NDT, \%}).$$

A positive error means that the EM instrument operator overestimated the actual LBS; a negative error means that he underestimated the actual LBS.

The other important parameter is the *Standard Deviation*, S, of a sample of n data points. Its value is:

$$S = \left[\frac{1}{(n-1)} \sum_{i=1}^{n} (X_i - \overline{X})^2\right]^{\frac{1}{2}}$$

Its square, S^2, is the Variance of the sample values, in statistical terms.

It might be useful to illustrate the meaning of these basic terms in a simple form, by noting that:

(1) in case of data points 5, 4, and 3, $\overline{X} = 4$ and S=1.000;
(2) in case of data points 12, 10, and 8, $\overline{X} = 10.000$ and S=2.000;
(3) in case of data points 4, 4, 4, 4, 4, and 4 (somewhat in line with values of current interest) $\overline{X} = 4.000$ and S=0.000; and
(4) in case of data points 4, 3, 2, -2, -3, and -4, $\overline{X} = 0.000$ and S=3.405877.

It can also be shown that:

(a) 50% of all random samples, from a population that has a normal distribution, fall within $\pm 0.674S$ of $\overline{X}$;
(b) 68.3% of all random samples, from a population that has a normal distribution, fall within $\pm 1S$ of $\overline{X}$;
(c) 95.4% of all random samples, from a population that has a normal distribution, fall within $\pm 2S$ of $\overline{X}$; and
(d) 99.7% of all random samples, from a population that has a normal distribution, fall within $\pm 3S$ of $\overline{X}$.

Histograms and approximating normal curves (i.e., curves that correspond to a population that has a normal distribution, with the same $\overline{X}$ and S values as the Table 1 sample) are shown in Figures 1 to 7. The term "acceptable" is being used in the sense of Ontario's Performance Requirements. The curves clearly indicate that Ontario's $\pm 4\%$ Performance Requirement is far from being satisfied.

On the basis of the analysed data, and of tables contained in authoritative publications by eminent statisticians (Pearson and Hartley 1966) the following can, however, be predicted at a 95% confidence level:

<u>In case of Locked-coil ropes</u>

(a) and the Rotesco AC instrument
some 28% to 46% of all future random test results will be "acceptable";

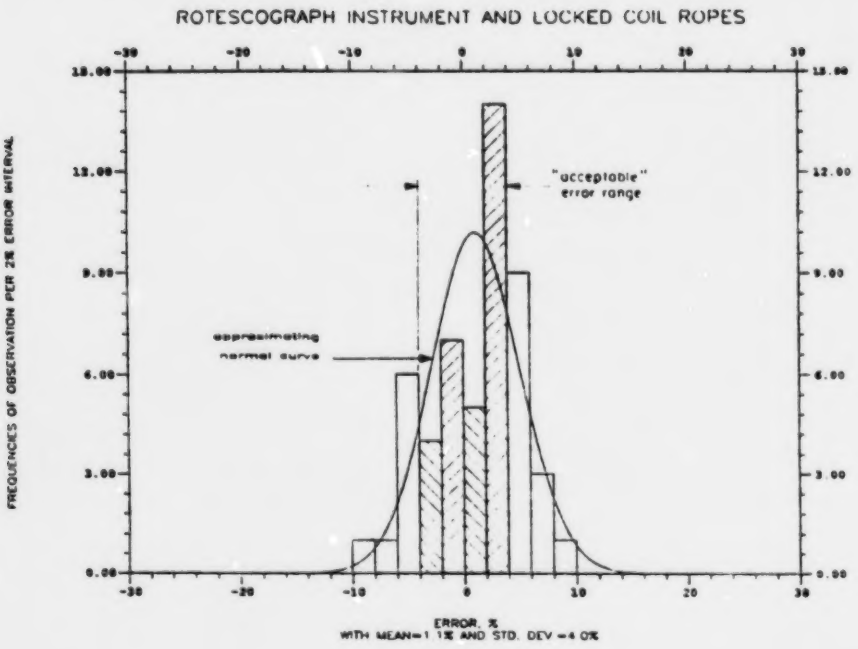
ROTESCOGRAPH INSTRUMENT AND LOCKED COIL ROPES
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
"acceptable" error range
approximating normal curve
ERROR, %
WITH MEAN=1.1% AND STD. DEV =4.0%

Fig. 2 — Error% vs frequencies of observation (51 altogether), and the approximating normal curve — locked coil ropes and Rotescograph instrument

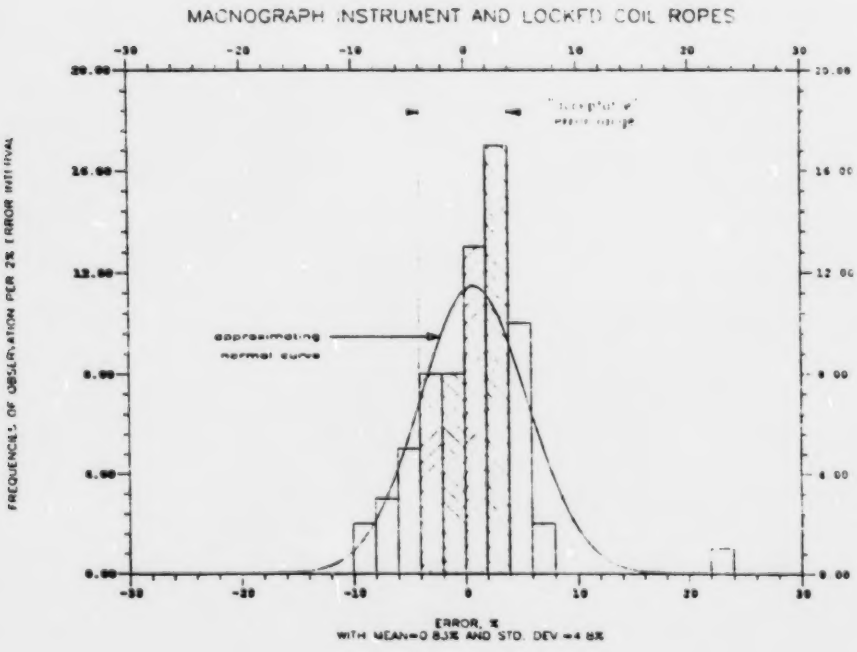

Fig. 3 — Error% vs frequencies of observation (69 altogether), and the approximating normal curve — locked coil ropes and Magnograph instrument

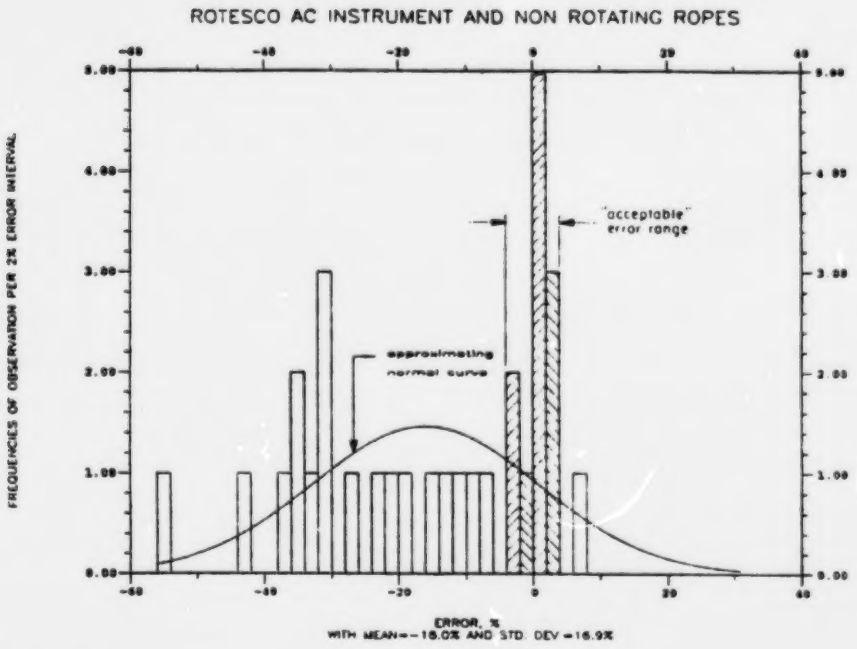
ROTESCO AC INSTRUMENT AND NON ROTATING ROPES
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
"acceptable" error range
approximating normal curve
ERROR, %
WITH MEAN=-16.0% AND STD. DEV=16.9%

Fig. 4 — Error% vs frequencies of observation (31 altogether), and the approximating normal curve — non-rotating ropes and Rotesco AC instrument

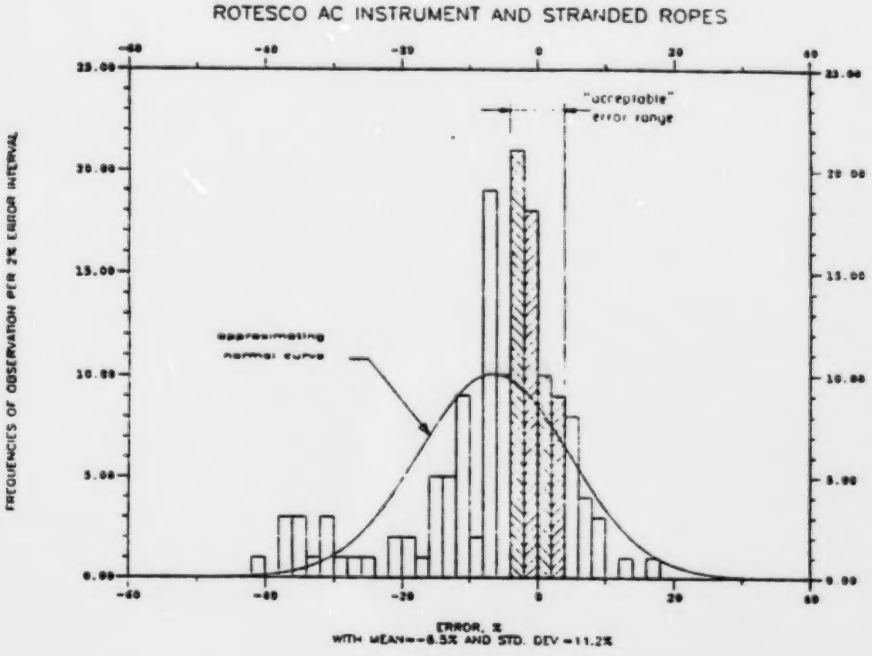
ROTESCO AC INSTRUMENT AND STRANDED ROPES
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
"acceptable" error range
approximating normal curve
ERROR, %
WITH MEAN=-8.5% AND STD. DEV=11.2%

Fig. 5 — Error% vs frequencies of observation (144 altogether), and the approximating normal curve — stranded ropes and Rotesco AC instrument

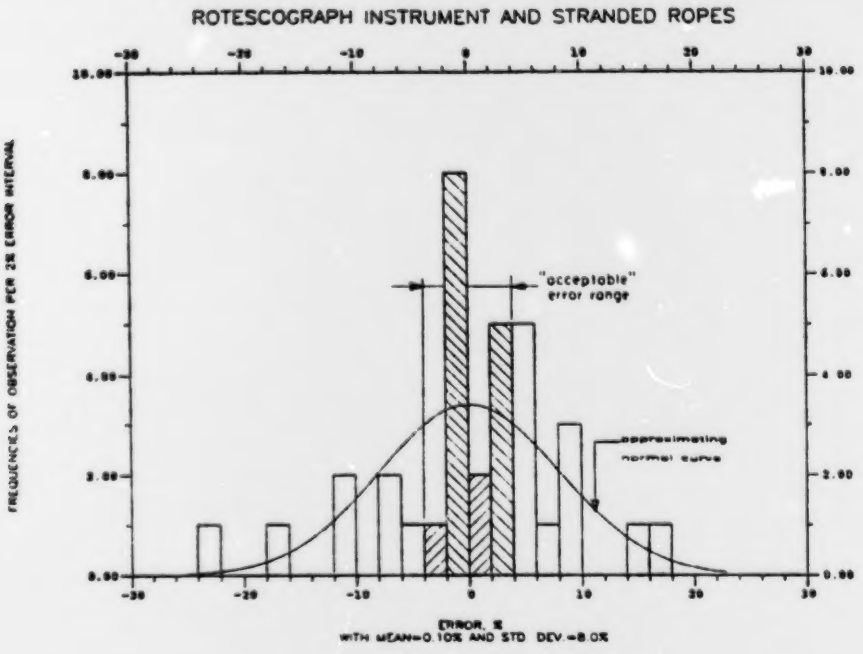
ROTESCOGRAPH INSTRUMENT AND STRANDED ROPES
"acceptable" error range
approximating normal curve
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
ERROR, %
WITH MEAN=0.10% AND STD DEV =8.0%

Fig. 6 — Error% vs frequencies of observation (34 altogether), and the approximating normal curve — stranded ropes and Rotescograph instrument

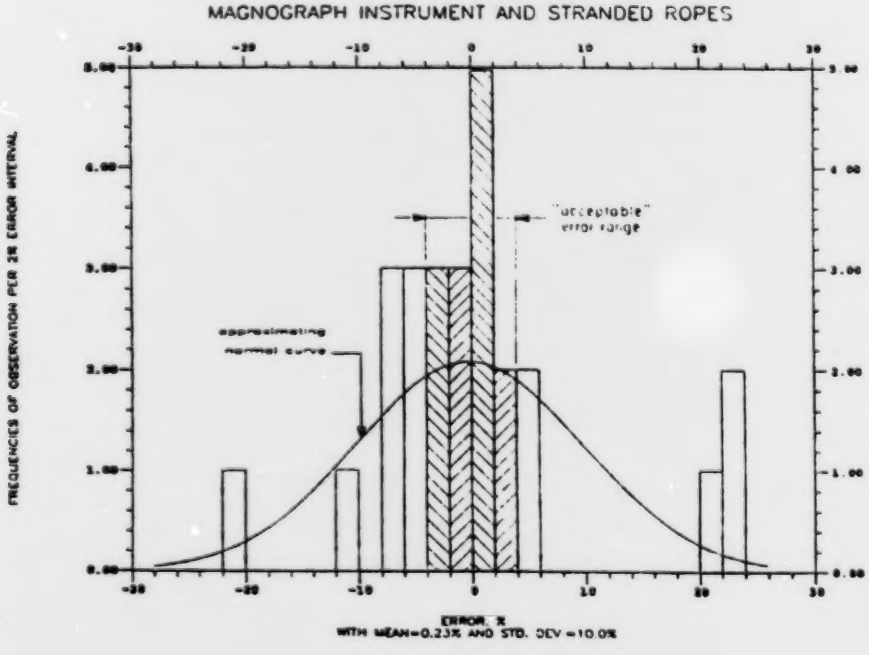
MAGNOGRAPH INSTRUMENT AND STRANDED ROPES
"acceptable" error range
approximating normal curve
FREQUENCIES OF OBSERVATION PER 2% ERROR INTERVAL
ERROR, %
WITH MEAN=0.23% AND STD. DEV =10.0%

Fig. 7 — Error% vs frequencies of observation (26 altogether), and the approximating normal curve — stranded ropes and Magnograph instrument

(b) and the Magnograph instrument
some 52% to 73% of all future random test results will be "acceptable".

(c) and the Rotescograph instrument
some 50% to 78% of all future random test results will be "acceptable";

In case of Non-rotating ropes

(a) and the Rotesco AC instrument
some 18% to 51% of all future random test results will be "acceptable";

(b) and the Magnograph instrument
some 40% to 99% of all future random test results will be "acceptable".

In case of Stranded ropes

(a) and the Rotesco AC instrument
some 30% to 46% of all future random test results will be "acceptable";

(b) and the Magnograph instrument
some 30% to 70% of all future random test results will be "acceptable".

(c) and the Rotescograph instrument
some 39% to 73% of all future random test results will be "acceptable".

(2) Special case — rope failures

Complete details of these special cases can not be reviewed here, for lack of space. We can, however, list the NDT estimates (a) recorded on the ultimate routine testing occasion before failure (NDT_{ult}), (b) obtained post-failure (NDT_{after}) on the failed rope, or (c) obtained on companion ropes of the ones that actually failed, i.e., on ropes that sustained an equal amount of loading, under identical conditions (NDT_{comp}). We noted the following:

Locked coil ropes

We have no record of an actual rope failure with these rope constructions.

Non-rotating ropes

(a) a 1 in. 18 × 7 rope. $NDT_{ult} = -5.5\%$;
(b) a $1\frac{1}{4}$ in. 34 × 7 rope. $NDT_{comp} = -5.0\%$; $NDT_{after} = -11.0\%$;
(c) a $1\frac{7}{32}$ in. 34 × 7 rope. $NDT_{comp} = -16.0\%$;
(d) a $1\frac{3}{4}$ in. 34 × 7 rope. $NDT_{ult1} = -14.0\%$; $NDT_{ult2} = -27.0\%$;
(e) a $1\frac{3}{4}$ in. 34 × 7 rope. $NDT_{ult} = -10.0\%$;

Stranded ropes

(a) a $2\frac{1}{4}$ in. 6 × 7 rope. NDT_{comp} = -4.5%;
(b) a $2\frac{1}{8}$ in. 6 × 7 rope. NDT_{comp} = -12.0%;
(c) a 2.29 in. 6 × 7 rope. NDT_{comp} = -2.5%;
(d) a 2.29 in. 6 × 7 rope. NDT_{comp} = -4.0%;
(e) a $1\frac{3}{4}$ in. 6 × 27 rope. NDT_{comp} = -2.5%;

The foregoing are examples of the unfortunate results that have arisen as a consequence of the uncertainty that is inherent in the current inspection cum evaluation systems.

(3) Special case — Estimating Errors (errors, %) in excess of 20%

The relatively low number of data points available for the non-rotating rope constructions makes their analysis somewhat less meaningful than that of the two other rope constructions. It can also be said that the extremely localized type of defects that characterize these ropes in a number of cases, makes their NDT examination particularly difficult. As an example: of the 31 data-pairs obtained with the Rotesco AC instrument, 12 (i.e., 39%) underestimated the "true" BSL by no less than 24%. The worst error amounted to -54.6%, with an average error of -35%. This situation is reflected in the substantial values of $\overline{X}$ and S, listed in Table 1. Moreover, in all of these cases the "true" strength losses themselves exceeded 32%, reaching a maximum of some 61% (with an average of 46%).

A similar review of the NDT test results obtained on stranded ropes shows that of the 144 Rotesco AC estimates 11% underestimated the "true" LBS by no less than 22%. Among this group the worst error amounted to -40%, and the average error to -32%. Also, in all of these cases, the "true" LBS values exceeded 26%, reaching a maximum of some 68% (with an average of 43%).

Among the 34 Rotescograph data only one serious (-23%) estimating error was noted. Here too the "true" LBS was very large (68%).

Of the much smaller (26 data-pairs) Magnograph sample with stranded ropes, only one underestimated, and three overestimated, the "true" LBS by no less than 22%.

In case of locked-coil ropes our review showed that:

(a) with the AC instrument 4% of the 113 data-pairs underestimated the "true" LBS by a substantial amount (from 20% to 27%). Here again the "true" LBS was substantial, ranging from 28% to 35%;
(b) with the Magnograph one serious (+23%) estimating error was noted. It, however, was an over-, rather than an under-estimate of the LBS;

(c) no serious estimating error was recorded with the Rotescograph.

From the foregoing it is clear that LBS estimates on the basis of EM instrument chart-traces can be badly in error, especially once the "true" LBS is substantial, and in case of certain rope constructions (NR) and rope defects (corrosion).

(4) Special case — NDT=0

In case of the locked-coil ropes in particular, but elsewhere as well, we noted a number of test data that indicate no estimated strength losses (i.e., NDT=0); yet they are coupled with extensive service histories, and often even with increased DT values. In these cases the true picture was only obtained by examining other test results as well, such as the rope's loss of extension, loss of rotation resistance of the wires, and whenever possible, hardening of the wires. We think that the loss of rotation resistance, in particular, should always be included in the laboratory tests of rope samples, since it is a relatively simple and straightforward experiment, yet one that yields valuable information, e.g., as to the work-hardening and/or fatigue condition of the rope.

In view of all the abovenoted uncertainties inherent in the determination of strength-loss values on the basis of NDT measurements, we decided to examine the following questions:

(a) if retirement criteria on the basis of LBS cannot be met with presently available instrumentation, could an LMA based requirement be better satisfied;

(b) how prevalent is the regulatory requirement of having to retire mine-shaft ropes, inter alia, on the basis of NDT determined strength loss estimates;

(c) can such requirements be reasonably well satisfied with presently available EM testers.

Our answers to the foregoing questions follow hereunder.

(a) Feasibility of accurately predicting LMA on the basis of EM testing

The 1978 Sheffield report (Commission 1978, Safety 1981) provided an excellent insight into the capabilities of a number of EM testers to detect LF in various rope constructions. LMA is the other chart-trace displayed by many EM instruments. It might, perhaps, be considered to be a more natural choice than LBS, upon which to base regulatory requirements. Very little has, however, been published about how the "true" and "estimated" LMA data compare in case of operational mine-shaft ropes, perhaps

because it is much more difficult to ascertain the "true" LMA of an operational mine-shaft rope, than it is to determine its LBS. True LMA is determined by dismantling the rope and measuring the diameter of each wire. We list hereunder some relevant data obtained, primarily, by ourselves in our Spokane (SRC) and Pittsburgh (PRC) Research Centres, and during our mine-site activities.

Laboratory tests

The Rotesco AC instrument

Metallic area change measurements were made at the SRC using a moving, spliced loop of $\frac{3}{4}$ in., 6 × 25 FC test rope (Ruff and Anderson 1987) with a total metallic area of 0.2032 $in.^2$. Results include the following:

(1) in case of a driving frequency of 10 HZ, and a rope speed of 80 fpm, only some 61% and 56% of the actual metallic area changes of 0.82% and 2.47%, respectively, were recorded (these area changes were obtained by adding 30 in. lengths of 0.046 in. diam, and of 0.080 in., crown wires, respectively, to the rope). On increasing the rope speed to 200 fpm, some 95% and 65% of the same actual area changes were recorded.

(2) for the same rope and same actual area changes, but a driving frequency of 30 HZ, the corresponding values were: 44% and 52% of the actual area increase recorded at 80 fpm; 67% and 51% of actual change recorded at 200 fpm; and 71% and 47% of the actual area change recorded at 400 fpm.

The Rotescograph instrument

Our results at the SRC (Anderson and Farley 1987) with the same $\frac{3}{4}$ in., 6 × 25 rope, as was used with the Rotesco AC tester, include the following:

(1) with a 0.82% actual area change and an 80 fpm rope speed, a $\frac{1}{4}$ in. added length was the shortest depicted by the LF trace — however, the shortest wire that could be resolved under these circumstances by the instrument into a constant trace output was 10 in.; in case of a 2.47% actual area change and 80 fpm rope speed the respective shortest length that had to be added so as to be recorded by the LF trace was $\frac{3}{16}$ in. — with a 10 in. length again being necessary before the instrument could produce a constant trace output;

(2) at a rope speed of 80 fpm, some 73% and 61% of the actual metallic area changes of 0.82% and 2.47%, respectively, were recorded (area changes obtained as with the Rotesco AC instrument tests);

(3) at 200 fpm the LF trace is similar to the one obtained at 80 fpm;

(4) as to the recorded MA changes — for the same rope, and for the same actual area changes as referred to in point (2) above, but at a rope speed of 200 fpm — the corresponding values are: 61% and 57% of the actual area increase;

(5) at 400 fpm rope speed the results were similar to those referred to in points (1) to (4) above;

(6) our tests indicate that at rope speeds of 80 fpm, 200 fpm, and 400 fpm, a 2 in. long area change of either 0.79% or 1.09% is the shortest that can be detected. As to the accuracy of measuring the LMA of 1 in./0.3 in. metal bars, it was found that in the best case some 80% of the actual area change could be detected.

The Magnograph instrument

(1) a report by the original designers of this instrument (Kitzinger and Naud 1978) states that "a loss of metallic area as small as 0.5% can be detected by the Magnograph";

(2) elsewhere it has been said (Haller 1984) that an accuracy of about $\pm 2\%$ of the rope's cross sectional area should be achievable with present day EM instruments;

(3) our tests indicate that at a rope speed of 80 fpm, 200 fpm, and 400 fpm, an 8 in. long area change of either 0.79% or 1.09% is the shortest that can be detected;

(4) at the PRC we conducted a comprehensive examination of a 2 in. 6 × 25 IWRC wire rope, 853 ft long, that had been run on the bending-fatigue machine until many broken wires appeared in the middle section of the rope. This machine is designed to deteriorate a rope to varying degrees along its length. Distances were carefully marked along the rope and, based on LMA traces produced by a Magnograph service representative, sections were selected for testing. The rope diameter was measured, under load, on each section; then 17 samples were cut from the rope. Figure 8 shows the metallic area losses calculated from the measured diameters, compared to the losses obtained from the Magnograph LMA traces. As can be seen, the agreement between them is fairly good on the first half of the rope, and very good on the last half. The conclusion to be drawn is

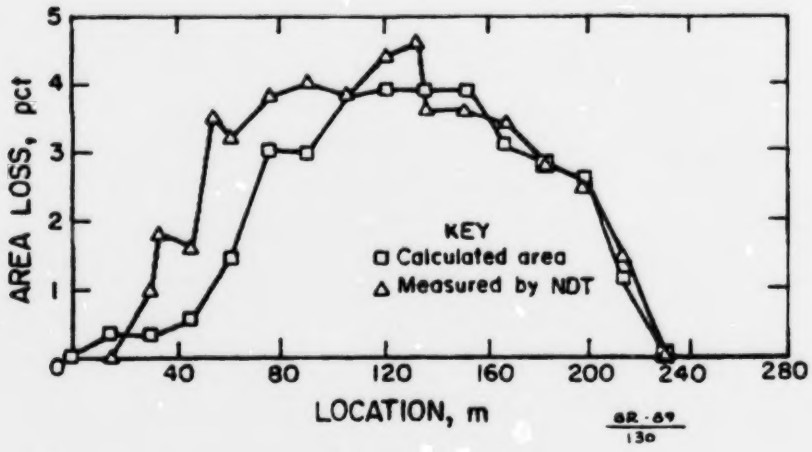

Fig. 8 — Calculated "true" area losses vs Magnograph estimates in a 2 in. 6 × 25 wire rope

that the instrument measured the area loss as well as the more laborious diameter measurement method.

Our abovenoted PRC comprehensive test series included both LMA and LBS measurements. Results of the latter tests are listed in Table 3. The last two samples, taken from the drum end of the rope, were used as the basis for comparing the data. It can be seen that the lowest values occur in the 394 to 492 ft rope section. Breaking strain is reduced by 65%, and the torque-constant (TC) is down by 11%, indicating increased hardness of the rope. TC is the slope of the line relating torque to load. The LBS of the rope is shown in Figure 9.

Although in this case we did not obtain comparative NDT estimates of the rope's strength-loss values, the LBS results are both noteworthy and pertinent. They show that the rope goes through three phases of degradation: (1) strength reduction due to metallic area loss, (2) strength increase due to cold working, and finally (3) serious strength loss due to fatigue failure of the wires. Degradation is symmetrical about the middle of the rope. In case of this rope, the 394 to 492 ft zone had so many broken wires that the LF trace was unintelligible. Normally, of course, a rope would be retired long before that many wires were broken. It would appear from these data, as well as from the NDT=0 special case referred to earlier, that measurement of metal hardness would be a valuable supplement in assessing the condition of a mine-shaft rope.

The LMA 250 series EM tester

Although the U.S. designed and built LMA series instrument was not used for any of the test runs recorded in the OML's data-bank, a limited amount of data were available

Table 3

Tensile test data on bending fatigue samples

Distance (m)	Breaking load (kg)	Breaking strain (%, $\frac{m}{m}$)	Torque constant, TC ($\frac{g\ m}{kg}$)
33.5 - 38.7	170.68	2.30	4.49
50.3 - 55.5	176.62	2.15	4.23
57.9 - 63.1	174.76	2.06	4.24
74.7 - 79.9	188.40	2.23	3.96
91.5 - 96.6	189.61	2.30	3.98
108.2 - 113.4	175.07	1.84	4.04
115.9 - 121.0	171.35	1.73	3.99
124.4 - 129.6	165.46	1.65	4.01
131.4 - 136.3	159.61	1.52	4.02
139.0 - 143.9	167.09	1.78	4.05
146.3 - 151.5	152.78	1.43	4.04
160.1 - 165.2	185.84	2.18	4.03
176.8 - 182.0	186.41	2.16	4.03
196.6 - 201.8	177.28	1.85	4.11
221.0 - 226.2	176.35	2.32	4.32
236.3 - 241.5	187.52	4.43	4.52
253.0 - 258.2	187.66	4.19	4.45

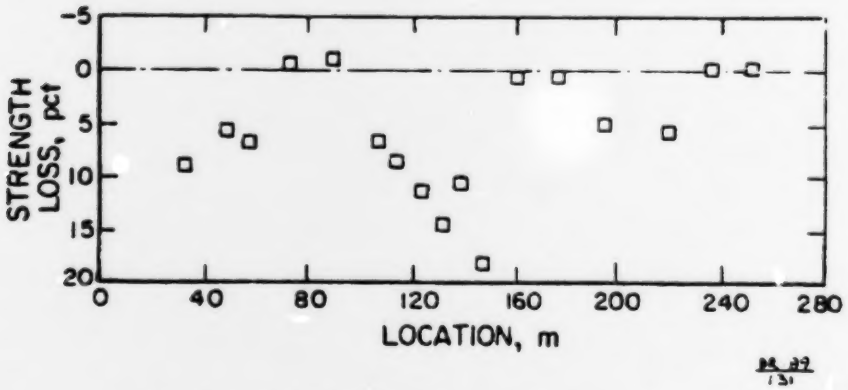

Fig. 9 — % LBS vs position along the rope

to us, primarily on the basis of tests in the U.S.A. As an example we noted that with this instrument a 1 in. long (in some cases even 0.5 in. long) area change could be recorded — whether the MA change was 0.79% or 1.09% of the total rope MA — at

both the 80fpm and 400 fpm rope speeds. Moreover, the best accuracy with which the LMA of 1 in./0.3 in. metal bars was measured amounted to an 85% record of the actual LMA.

Field tests

While our foregoing laboratory LMA results are encouraging, some of the in situ test results need also to be listed. As an example we observed that LMA estimates obtained with a Magnograph and an LMA 250 tester on the same operational mine-shaft ropes (one a $1\frac{1}{4}$ in. LC, the other a $1\frac{7}{8}$ in. NR construction), differed by more than 100%. Moreover, the greater estimate was not obtained consistently with any one of these intruments. Another example involved field-tests on a 1 in. 6×26 RRL wire-rope (Poffenroth and Sheridan 1986). In this case the in situ loss of metallic area data were obtained with a Rotesco AC tester. On comparing these with the actual LMA values, it was found that the actual area losses were some 100% greater than had been estimated on the basis of the EM traces.

On reviewing these data we cannot, therefore, say with any degree of certainty that the EM instrument's LMA-trace based rope retirement criteria are, *ipso facto*, any more reliable than the LBS based ones. We shall re-examine this question as soon as the results of a Canadian research project, currently underway (Geller et al 1988) become available. We also suggest that much additional information could be obtained in this context, at no extra cost, if the regulatory authorities would specify (1) that all EM test reports are to contain separate sections on the observed/estimated LF, LMA, and LBS values, and (2) that the exact location of the rope samples, submitted on a routine basis for regulatory destructive testing, be precisely identified.

(b) "Approval", "competency", and LBS based EM testing requirements

We reviewed a number of rope retirement criteria (Geller et al 1988) and found an extraordinarily wide range of regulatory requirements. These include the situation in Britain, with no mandatory EM testing at all, as well as those in many Canadian provinces, where EM testing with an *approved* instrument by *competent* operators is the rule. On balance we find that at present few, if any, European, but many North American mining acts include EM instrument based LBS determination among their mine-shaft rope retirement criteria. However, we also note that in some Canadian Provinces new regulations are now being considered that will be based: (a) on NDT determined LMA, and/or (b) on reduction of diameter, and/or (c) on diameter reduction based calculations (Geller et al 1988), rather than on NDT based LBS values.

Regarding the widespread — but by no means nationwide — Canadian regulatory requirement specifying that EM instruments must be "approved": in this context some

appropriate comments (Weischedel 1985) may be quoted: *Only the Canadian government requires approval of rope inspection equipment. Neither the U.S. government, nor any other government, worldwide, requires or grants instrument certification.* Or, to quote another relevant comment (Dixon 1988): *It is notable that specific approval of method, equipment, and operator are cited in a number of Canadian provincial regulations. In most fields of NDT the problem is dealt with by defining carefully the physical basis of the method, in proprietary or concensus standards for test methods, and by widely recognized inspector qualification schemes. The general principles of quality assurance are then used to ensure that qualified personnel (whose qualifications depend in part on a fundamental understanding of the physical basis of the test method) use test methods that can be demonstrated to conform to the relevant standards. Reliance is still placed on operator judgement, but steps have thus been taken to ensure that the inspection is done in a recognized manner, and the operator had somewhat more than a superficial training in equipment adjustment and matching observations to examples.*

We too are well aware that the "approval" requirement is not customary elsewhere. As an example:

(1) in one of West Germany's most heavily industrialized area, Nordrhein-Westfalen, the mine-inspectorate does not specifically elaborate these matters. In practice, however, EM instrumentation is designed in-house, by a group of experts from an industry cum state supported independent rope-research organization. They also undertake EM testing in the field. This group is composed of people whose knowledge covers the entire spectrum of general mining, and specifically hoisting related, problem areas — including the complete history of the presently installed, plus previously used, wire-ropes (from manufacturing, through installation and operation, up to retirement) the loading and general shaft conditions, etc. All final decisions are based on a group consensus, rather than on individual opinions.

(2) in Hungary too, the mining authorities accept the expertise of a selected group of people. In this case it is a University Faculty, who themselves decide on the type of EM instrumentation to be used. They, in turn, can also recommend that others be acknowledged as "qualified" operators, such as large mining organizations, for example.

(3) U.S. authorities leave the choice of EM instrument to the users themselves;

(4) in Britain EM testing itself is not mandated, nor the make of EM tester that is to be used;

(5) with the *Swiss Federal Laboratories for Materials Testing and Research (EMPA)* the practice is to only use an EM tester as a means for locating all rope defects, and to evaluate them as to their severity and relative importance. Emphasis

is then placed upon subsequent visual examination of any major defects thus detected. The inspectors are specially trained for their job, with a very good knowledge of wire-ropes in general. Moreover, every instrument chart is double-checked by a second inspector. As a result, only some 0.5% of inspected ropes need reinspecting.

Perhaps in Canada too, some of the pertinent regulatory requirements might be modified in future, as is the case with certain draft versions of the regulations, currently under review (Geller et al 1988).

As for requiring operator competency in the regulations, we believe that the EM tester's mechanical operation is not unduly difficult to learn. However, evaluation of the EM instrument charts cannot, at this time, be based on purely mechanical operations. The crux of the problem is to be thoroughly knowledgeable about the history of the rope in question, and of that of its predecessors. To illustrate: in Canada there are at least two major mining organizations who own and operate their own EM testers (two Rotesco AC and a Rotescograph, respectively). Results are correspondingly favourable. As an example: of the 34 data-pairs listed in Table 1 for stranded ropes and the Rotescograph instrument, 23 (68%) were obtained by one of these mining companies. Of these 78% were "acceptable", in the sense used elsewhere in this report. Even of the 9 cases with a " true" LBS $\geq$ 10% (ranging from strength losses of 10% to 31%), only two involved an error in excess of 4%, and even these two erred on the safe side, i.e., they were over-, rather than under-estimates of the "true" LBS.

(c) Feasibility of accurately predicting LBS on the basis of EM testing

This requirement might be theoretically possible to achieve. We are, however, aware of the serious difficulties in predicting LBS on the basis of LMA and LF data, which are the only ones currently recorded on the EM instrument charts. We think that these instruments are powerful tools in assessing the wire-rope condition, provided the LF and LMA recordings are accurate and sufficiently well defined, and the data evaluation technique is sound. Even so, supplemental data, such as hardness and/or rotation resistance of the wires must often also be considered. We prefer not to answer this question in further detail at this point. We shall re-examine it as soon as additional data are available as a result of contracted work that is currently proceeding with Canadian funding (Geller et al 1988).

CONCLUSIONS

In summary we note that the benchmark requirement of being able to estimate the breaking strength loss of mine-shaft wire-ropes with an accuracy of $\pm 4\%$ at a level of

confidence of 95%, — on the basis of in situ non-destructive tests with EM instruments, combined with procedures currently used by the operators to interpret their instrument readings — has not been achieved with any of the commercially available instruments we analysed. All the same we do not necessarily believe that this goal cannot be attained in the future.

The number of seriously flawed NDT estimates has also been noted, and the number of rope failures that occurred in spite of routine EM testing. Even in cases where no rope failures occurred, the actual breaking strength losses in the retired ropes greatly exceed — on a number of occasions — the ones allowed for by regulations.

We also note that the EM instrument-based estimates of metallic-area losses are not as reliable as would be desirable, at any rate not in all cases analysed. We hope to be able to obtain additional significant data as a result of a project currently in progress in Canada.

We believe that the NDT test reports should always contain a clear indication of the LF, of the LMA, as well as of the LBS values that have been estimated on the basis of the chart traces. Another suggestion is that the exact location of the rope samples that must be tested destructively — on a routine regulatory basis anyway —- be stated. This way the store of comparative NDT/DT data-pairs could be increased, at no extra cost, on all those occasions when these rope samples originate from a section of the wire-rope that has also been tested non-destructively (again on the occasion of a routine regulatory examination). Of course this store of valuable information will also have to be analysed and published at regular intervals. Finally we suggest that the rotation resistance of the wires be tested as often as possible by all those laboratories concerned with the type of problems we are discussing in this paper.

While there is room for further improvements, and in spite of the abovenoted shortcomings, we maintain that the safety of mine-shaft hoisting has increased manifold since the worldwide acceptance of regular NDT testing with the EM instruments. As mentioned, the Rotesco AC instrument was the first tester that found widespread use in the North American mining industry. Thereby it contributed substantially to this increase in mine-hoisting safety. However, as illustrated in Table 1, a subsequent generation of testers reduced uncertainty in evaluating fitness for continued service.

We are of the opinion that close national and international cooperation is most desirable, as has been amply proven by the Canada-U.S.A. joint project in which we are engaged. The extensive data-bank of the OML's Rope Testing Laboratory has supplied us with a wealth of invaluable information. We would be grateful to receive similar information from others, who might be reading this report with interest.

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